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LCoS display phase self-calibration method based on diffractive lens schemes

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A B S T R A C T

An experimental method to calibrate Liquid Crystal on Silicon (LCoS) displays by self-generating lens configurations on the studied device is proposed in this paper. On the one hand, a split-lens is displayed in the LCoS to self-generate an interference pattern from which the phase-voltage curve of the modulator is calculated. On the other hand, a microlens array is displayed on the LCoS, within a same experimental set-up, to implement a Shack-Hartmann (S-H) wavefront sensor, from which the display surface profile is retrieved. Specifically, by means of a feasible set-up, the proposed method allows measuring the deviation from flatness of the LCoS displays as well as to determine the phase-voltage response of phase-only SLMs. Experimental results demonstrate a linear tendency phase-voltage curve that ranges from 0 rad up to ∼6.28 rad, for the used light wavelength. Moreover, by extracting the LCoS phase distribution measured with the S-H configuration, the LCoS surface inhomogeneity is corrected by 95%.

1. Introduction

Liquid Crystal Display (LCD) is a mature technology widespread used in optical based applications. Thanks to their capability to spatially manipulate the phase properties of light beams, they are commonly used as Spatial Light Modulators (SLM) to manipulate the complex wavefront amplitude. For instance, they are applied in adaptive optics, to correct the wavefront aberration introduced by turbulence [1,2]; in metrology, to control phase distributions in interferometers [3,4]; in waveguide technology, to achieve wavelength selective switch systems, or to manipulate the lightwaves [5–7]. As the phase properties can be modified by controlling the voltages address to the SLM, LCDs are also commonly used in dynamic processes. For instance, for the generation of diffractive optical elements (DOEs) in diffractive optics applications [8,9]. They as well stand as important components in real-time laser beam shaping [10–12], and in structured illumination systems [13,14]. LCDs are also used to implement optical tweezers [15,16], digital lenses with improved performance [17,18], or optical encryption [19], etc.

Liquid Crystal on Silicon (LCoS) displays [20] are a class of LCD that work in reflective configuration. By selecting the proper input polarization [21], the LCoS performance can be optimized and we can select a phase-only or an amplitude-only regime. When using a phase-only configuration, the phase modulation can by digitally controlled by addressing a proper Diffractive Optical Element (DOE) to the LCoS. A number of improvements, such as high resolution, small pixel size, and very appealing fill factor (usually ∼90%), are presented when comparing these reflective devices with transmissive LCDs. More importantly, LCoS displays present a larger phase modulation than transmissive devices with the same thickness, as light performs a double pass into the display.

Although the above-stated applications highlight the important role that LCoS play in different fields, to work with these devices in optimal conditions, efficient calibration and optimization of the spatial light modulators are required. As a consequence of the large demand of applications requiring the use of LCD technology, a widespread number of optimization methods can be found in literature [16,22–30], most of them based on interferometry [24–26] or diffraction [27,28]. Some authors have demonstrated that diffractive based methods, which may be valid for other LCDs, are not suitable to be applied with LCoS displays [23], mainly due to the time-fluctuations of the phase phenomenon (also referred as flicker effect). Under this scenario, alternative optimizing

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methods were proposed to take into account this effect [29–33] and different strategies have also been reported to minimize the observed DOEs efficiency loss associated to large phase-fluctuations [34,35].

Another critical drawback present in LCDs, both working in transmissive or reflective configurations, is related to inhomogeneities in the display flatness. These spatial inhomogeneites (which are related to different causes, such as screen lateral stresses or glass thickness variations), introduce an extra spatial phase distribution that degrades the performance of the modulator. Thus, this extra phase distribution must be taken into account for a proper calibration. As a consequence, different experimental strategies have been proposed to measure the display profile in order to compensate the screen inhomogeneities [16,36–38].

Recently, the idea of self-calibrating LCDs was proposed by J. L. Martinez et al. [31] by the means of addressing some DOEs on the LCD. The self-calibrating approach presents some advantages compared with standard calibrating methods. For instance, they avoid the necessity of using additional optical elements (i.e., without requiring external optical arrangements –as the commonly used interferometry, diffraction or polarization based set-ups). In fact, the same LCD to be calibrated is employed to display the optical element that allows the measurement. In Ref. [31], the overall averaged phase modulation of the device was evaluated by simultaneously addressing two diffractive elements displayed on two different halves of the LCoS. In one half, a uniform image or 'piston' was displayed. Then, different constant gray levels were added to this image so that this part acted as a phase-shifting mirror. In the other half of the screen, a symmetric binary phase grating was displayed. By selecting the proper diffractive order generated by the grating, this second half acted as a tilted reference plane-wave that interfered with the wave coming from the 'piston'. Note that different gray levels added to the piston led to different displacements of the interference pattern, from which the overall phase modulation of the device was determined. The method was also used to spatially resolve the phase-voltage curve. Nevertheless, this approach does not provide the deformation of the screen. As stated above, a complete description of the modulator also requires taking into account the screen deformation.

In this work we provide an alternative self-calibration method, based on addressing different diffractive lens configurations, valid to both characterize the overall phase-gray level performance and the screen profile of LCDs. In particular, the self-generation of two different diffractive-lens based DOEs is proposed. The first one consists of addressing a split-lens configuration [14], which leads to a simple direct implementation of an interferometric system, from which the overall phase distribution as a function of the addressed voltage is obtained. It is worth to mention that this method is valid even in presence of time-fluctuations of the phase [23], because it is able to give the required average phase as a function of the applied voltage. Furthermore, by addressing a second diffractive pattern, it is also possible to self-determine the screen profile of the display without any modifications of the optical set-up. This is achieved by properly addressing an arrangement of dynamic microlenses to the LCoS display (Shack-Hartmann wavefront sensor configuration [39,40]) and performing an iterative scanning process. We want to note that the propose method not only allows providing a complete calibration of the LCoS, by simply self-addressing different DOEs, but also determining these important characteristics just by using the same feasible and compact experimental set-up.

The outline of this work is as follows. In Section 2, we describe the proof of concept of the method used to self-calibrate the phase-voltage curve of the LCoS. Next, in Section 3, we describe the technique based on a Shack-Hatmann configuration, used to perform the self-measurement of the LCoS screen profile. In addition, the generation of the microlens array system and the ulterior retrieving of the screen profile, from the local light focalizations, are discussed. Afterwards, the methods described in Sections 2 and 3 are experimentally implemented and the corresponding results are shown and discussed in Section 4. Finally, the main conclusions of the work are provided in Section 5.

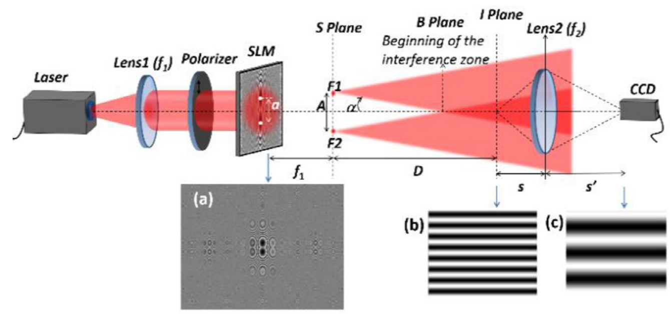

Fig. 1. Scheme of the optical set-up used to perform the phase-voltage calibration of the SLM.

2. LCoS phase-voltage self-calibration based on split lenses

In this section we describe a self-calibration method, based on split-lens configurations, to determine the phase-voltage curve of SLMs. This is an interferometic-based method, and thus, it is valid to be used even in presence of time-fluctuations of the phase [24], a non-desired phenomenon observed in some reflective LCoS displays.

The main idea consists of addressing a DOE to the LCoS in order to create a controlled interferometric pattern onto a propagated plane. In this way, the generated digital element replaces interferometric external set-ups commonly used to calibrate the phase-modulation of LCoS. In particular, we use as DOE the two-sectorial split-lens scheme described in Ref. [14]. This distribution is equivalent to the classical Billet lens configuration which consists of a lens split in two halves, and where the centers of those halves are transversally separated to a certain distance a. Under this scenario, each one of the two split-lens sectors leads to a focalization spot on the focal plane. These two light spots can be understood as two new coherent light sources that produce an interference fringe pattern onto a propagated plane. Although, in principle, this would be equivalent to the Young's experiment, in the Billet lens case the light passing through the separation between the two lens halves also adds a non-desired contribution in the interference pattern. This situation is solved by displaying a two-sectorial split lens onto a SLM, in a way that the corresponding phase distribution fully covers the modulator screen. Under this scenario, the composed diffractive lens gives place to two light spots at the focal plane, generating the interference fringes pattern at the far field [14]. What is more, some properties of the pattern can be digitally modified just by tuning few physical parameters of the system (e.g., the axial plane where the interference pattern is produced or the pattern period can be changed by tuning the focal length of the two split-lenses or the distance a between the halves centers, respectively).

A sketch of the optical set-up used to self-calibrate an SLM is shown in Fig. 1. A collimated polarized laser beam illuminates the SLM with the two-sector lens addressed on it, which give place to the generation of two focalization spots (F1 and F2 in Fig. 1) in the focal plane (S plane in Fig. 1). These two new light sources F1 and F2, with the same intensity, produce a fringes-like interference pattern in the far field. As it was previously pointed out, the properties of the split-lens (lens focal length, distance to the centers a, lens sectors orientation, etc.) are digitally controlled. An example of a particular phase distribution to be addressed to the SLM, corresponding to a lens split in two sectors vertically separated a distance a, can be seen in Fig. 1(a). As we are illuminating the SLM with a collimated beam, the two resulting sources F1 and F2 are separated a distance A equal to the selected distance a and to the same direction. This situation leads to horizontal fringes in a far field plane (e.g., I plane in Fig. 1). However, note that the direction of the fringes pattern could be controlled just by properly modifying the direction of separation between lens centers.